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OPTIMIZING READINESS AND EQUITY IN MARINE CORPS AVIATION TRAINING SCHEDULES

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The Marine Corps trains its aviation units according to a Training and Readiness (T&R) Program that quantifies combat readiness based on completion of prescribed sets of training "events" (e.g., aircraft training flights, tactical control of aircraft, simulator training, etc.). Efficient scheduling of these events is vital to wringing more readiness, i.e., combat power, from shrinking resources. Schedules assign individuals (pilots, naval flight officers, or air controllers) to events and time periods while satisfying T&R Program event sequence, event repetition, and qualification requirements. Secondary to readiness, units pursue equity of opportunity and workload among individuals to preserve morale and produce a wider base of fully combat-qualified warriors. This thesis develops a bicriteria mixed integer programming model that maximizes a combined function of readiness and equity over a time horizon of ninety days. The model enforces T&R Program requirements and personnel availability constraints. A schedule that includes equitability constraints is within 98.1% of optimal readiness, but reduces "inequity" by 79.9%. Schedules are typically created in 10 minutes on a personal computer.

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OPTIMIZING READINESS AND EQUITY IN MARINE CORPS AVIATION TRAINING SCHEDULES

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ABSTRACT

The Marine Corps trains its aviation units according to a Training and Readiness (T&R) Program that quantifies combat readiness based on completion of prescribed sets of training "events" (e.g., aircraft training flights, tactical control of aircraft, simulator training, etc.). Efficient scheduling of these events is vital to wringing more readiness, i.e., combat power, from shrinking resources. Schedules assign individuals (pilots, naval flight officers, or air controllers) to events and time periods while satisfying T&R Program event sequence, event repetition, and qualification requirements. Secondary to readiness, units pursue equity of opportunity and workload among individuals to preserve morale and produce a wider base of fully combat-qualified warriors. This thesis develops a bicriteria mixed integer programming model that maximizes a combined function of readiness and equity over a time horizon of ninety days. The model enforces T&R Program requirements and personnel availability constraints. A schedule that includes equitability constraints is within 98.1% of optimal readiness, but reduces "inequity" by 79.9%. Schedules are typically created in 10 minutes on a personal computer.

THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this thesis may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

Additionally, a portion of the analysis conducted for this thesis was performed using *APL2/PC* and *AGSS*. Naval Postgraduate School uses this program under a test agreement with IBM Research.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The U.S. Marine Corps trains its aviation units according to a Training and Readiness (T&R) Program directed and defined by the Commandant of the Marine Corps and implemented at the squadron level. The Program quantifies combat readiness and prescribes sets of training *events* (e.g., aircraft training flights, tactical control of aircraft, simulator training, etc.) that contribute to readiness. Units report their readiness as defined by the Program to various headquarters who monitor readiness and select units for combat. Efficient scheduling of training events is vital to wringing more readiness from limited and shrinking resources and providing greater combat power to commanders. Schedules assign individuals (pilots, naval flight officers, or air controllers) to events and time periods while satisfying Program event sequence, event repetition, and qualification requirements.

In addition to satisfying Program requirements, units also pursue equity of advancement opportunity and equity of workload among individuals to preserve morale and to produce a wider base of fully combat qualified warriors. Equity enhances readiness by reducing the chance that one or two casualties cripple a unit and expands corporate knowledge and experience. In addition, fair treatment motivates Marines to train harder, improving both individual and unit readiness. While equity's short-term effect on readiness is subtle, equity's long-term effect is an important element of effective training management.

This thesis develops a bicriteria mixed integer programming model that produces a ninety day training schedule that maximizes a combined function of readiness and equity.

Most Fleet Marine Force aviation units schedule, forecast, and plan training manually. Consequently, they cannot do a very good job of creating efficient and equitable schedules. Based on information stored in a training management database,

schedulers usually generate two types of schedules: "macro" and daily. One, two, or three month macro schedules are planning guides that indicate gross numbers of events, by type, to be accomplished by the unit within the time period. Due to the effort required, these schedules rarely assign an individual and event to a specific time period and may ignore many of the Program or personnel availability constraints. At the daily level, schedulers assign individuals to events and time periods, but check Program requirements and individual availability manually, for that day only. Because of the limitations discussed, both macro and daily schedules fall short of optimality and thus waste resources.

Previous efforts to improve upon manual scheduling have concentrated on optimizing either macro schedules or daily schedules. However, none of these tie together the time horizon of the macro schedule with the explicit assignments of the daily schedule. They optimally solve over-simplified versions of the problem. Others have attempted heuristic approaches to efficient scheduling through intelligent data presentation to the scheduler. In addition to producing inferior solutions, both duplicate some of the record-keeping features of the aviation training database currently in use.

This thesis develops a bicriteria mixed integer program that maximizes a combined function of readiness and equity over a time horizon of ninety days. The model enforces T&R Program policies and accounts for individual unavailability. The resulting schedule assigns individuals (pilots, Naval flight officers, or air controllers) to events and time periods while satisfying Program event sequence, event repetition, and qualification requirements. In addition to the schedule, output identifies unused personnel in each time period, projected individual and unit readiness gains, resulting readiness levels, and events unscheduled due to lack of personnel.

With parameters established during testing, the model is generated and solved on a personal computer in under 10 minutes. The model is successful in optimizing a

weighted combination of readiness and equity (weights determined by the user) in the schedules it produces. Scheduling with the model on a PC is much faster than manual scheduling. It uses input from an existing automated database and produces other useful information that was previously generated and maintained manually for the purpose of training management. With explicit individual-event-time period assignments, the schedule provides planners with much more information than is available using heuristically derived macro schedules.

I. MANAGING MARINE AVIATION TRAINING

The U.S. Marine Corps trains its aviation units according to a Training and Readiness (T&R) Program (Commandant of the Marine Corps, 1988) that quantifies combat *readiness* (a measure of combat proficiency) and prescribes sets of training *events* (e.g., aircraft training flights, tactical control of aircraft, simulator training, etc.). Units report their readiness as defined by the Program, to various headquarters who monitor readiness and select units for combat. Efficient scheduling of training events is vital to wringing more readiness from limited, shrinking resources and providing greater combat power to commanders. These schedules assign individuals (pilots, naval flight officers, or air controllers) to events and time periods (week, day, half-day periods, etc., depending upon the time horizon) while satisfying Program event sequence, event repetition, and qualification requirements. Secondary to readiness, units pursue equity of opportunity and workload among individuals to preserve morale and produce a wider base of fully combat qualified warriors. This thesis develops a bicriteria mixed integer programming model that produces a ninety day training schedule that maximizes a combination of unit readiness and equity, given a fixed set of events. This Chapter relates the background necessary to understand the issues involved in T&R Program scheduling and shows the need for the proposed, improved scheduling methods.

A. MARINE AVIATION TRAINING AND READINESS PROGRAM

The Commandant of the Marine Corps has directed and outlined a U. S. Marine Corps Aviation T&R Program to be implemented at the squadron level. The Program quantifies individual readiness and defines training events that contribute to readiness. Within the Program, sequences of events lead to qualifications that reflect increasing combat readiness. Additionally the Program outlines minimum subsets of events necessary to maintain qualification and the frequencies at which the events must be repeated. This Program defines the scheduling problem. Understanding the purpose,

breadth, current execution, and the main management tasks of the Program, provides insight into the model proposed in this thesis.

1. Purpose of Marine Aviation Training

Marine Corps aircraft and aviation command and control (C^2) squadrons conduct training missions that prepare Marines to execute the squadrons' functions in combat. Training maintains or increases Military Occupational Specialty (MOS) proficiency and qualification and thereby sustains or improves squadron combat readiness. Since training resources (aircraft, fuel, funds, training areas, crews, etc.) are limited, efficient training management is a vital component of maximizing unit readiness. To standardize, implement, and measure aviation training, the Marine Corps has established a T&R Program that is managed at the squadron level within the Fleet Marine Force (FMF).

2. Units Subject to Marine Aviation Training Programs

All seventy-one FMF aircraft and aviation C^2 squadrons manage training programs in compliance with the T&R Program. Of these seventy-one squadrons, thirty are fixed-wing, thirty are rotary-wing, and eleven are C^2. These three categories are further divisible by aircraft type or C^2 function. Fixed-wing squadrons operate F/A-18A/C, F/A-18D, AV-8B, EA-6B, or KC-130 aircraft. Rotary-wing squadrons employ CH-46G, CH-53D, CH-53E, UH-1N, and AH-1W helicopters. C^2 squadrons perform Air Command, Air Defense Control, Air Support Control, or Air Traffic Control. In each of these units the technical training of one or more MOSs related to aircraft operation, or C^2 performance, is governed by the T&R Program.

3. Measure of Effectiveness

The Combat Readiness Percentage (CRP) (ranging from 60% to 100% in FMF units) is the T&R Program measure of effectiveness that indicates the level of proficiency and qualification held by an individual Marine. Under the T&R Program, an individual is Combat Capable and assigned a CRP of 60% upon completion of entry-

level MOS school. An individual in an FMF squadron, after reaching Full Combat Qualification in all areas, earns a 100% CRP. The average CRP of all individuals in a unit gauges its readiness.

4. Aviation Training and Readiness Manual (T&R Manual)

The T&R Manual is a Marine Corps Order that directs and defines the T&R programs managed by the squadrons. It dictates the assignment policies and event values used by squadrons to create schedules. For each MOS within the T&R Manual, a different chapter defines training events that contribute to readiness, the relative contribution of each event, sequences of events that lead to qualification, and qualifications that must be attained to reach Full Combat Qualification. Additionally, the T&R Manual outlines minimum subsets of events, and the frequencies at which the events must be repeated, to maintain qualification. The T&R establishes the structure of Marine aviation training management.

5. Aviation Training Information Management System (ATRIMS)

As late as the early 1990s, some units still maintained a system of manual greaseboards to record and display training data. Now, squadrons maintain an automated database of training management data called "ATRIMS." This database contains or calculates information that facilitates event scheduling and readiness monitoring; e.g., lists of events completed by each individual, individual CRPs, time remaining before an individual loses *currency* (is considered no longer proficient) in an event, etc. ATRIMS uses values and relationships listed in the T&R Manual to make calculations. ATRIMS automates maintenance and calculation of training data, and thereby aids trainers and schedulers managing the T&R programs.

6. T&R Program Management Tasks

Effective T&R Program management requires execution of four main tasks: efficient scheduling, forecasting readiness, determining training requirements to meet

readiness goals, and planning personnel availability. The model described in this thesis contributes to accomplishing these tasks.

a. Efficient Scheduling

Efficient scheduling is the crux of effective Program implementation. Inefficient use of training resources through inefficient scheduling results in suboptimal readiness levels. Also, since units produce their own trainers, cumulative inefficiencies over time potentially result in fewer trainers to train new trainees. Therefore suboptimal scheduling robs units of readiness potential.

b. Forecasting Readiness

Commanders forecast readiness by estimating future readiness based on execution of a monthly, bi-monthly, or quarterly schedule. This enables the commander to identify weaknesses in future readiness levels and reallocate resources to ensure appropriate readiness levels can be attained by the appropriate units or individuals at the appropriate times. Accurate readiness forecasting depends upon accurate training and personnel availability forecasting.

c. Determining Training Requirements to Meet Readiness Goals

In determining training requirements, the unit commander identifies training that must take place to enable the unit to meet readiness goals or avoid drops in readiness. Gross requirements may often be estimated easily, and additional events that will produce the largest marginal benefit subsequently identified. However, exploitation of these opportunities may be constrained by personnel availability.

d. Planning Personnel Availability

Commanders plan personnel availability to get the most out of available resources. Extended schedules or plans that overlook day-to-day personnel availability often execute poorly as non-availability damps forecasted readiness. Whether planning

for personnel to be available for required events or planning events to take advantage of otherwise idle personnel, including day-to-day availability is necessary for efficient scheduling and effective Program implementation.

7. Equity

While not mandated by the T&R Manual, units attempt to achieve equity of opportunity and workload among individuals to enhance morale and to produce a broader base of qualified personnel. Equity enhances readiness by reducing the chance that one or two casualties will cripple a unit and by expanding corporate knowledge and experience. In addition, fair treatment motivates Marines to train harder, improving both individual and unit readiness. While equity's short-term effect on readiness is subtle, equity's long term effect is an important element of effective training management.

B. TRAINING MANAGEMENT STRUCTURE

All aviation training that falls under the authority of the T&R Manual shares the same basic structure. The T&R covers almost twenty MOSs that exist within seventy-one units. Each MOS has its own unique chapter (or *syllabus*) detailing specific requirements for MOS training. However, the underlying principles are identical. The following concepts and terms are defined in the T&R Manual and used in the model developed in this thesis.

1. Qualification and Designation

Within each syllabus, subsets of events (or *segments*) are categorized as Combat Capable Training, Combat Ready Training, Combat Qualified Training, Fully Combat Qualified Training, Instructor Training, and Special Training. Combat Capable Training occurs during entry level MOS school and accounts for the 60% baseline CRP at the beginning of FMF squadron training. Instructor and Special Training categories contain events that do not contribute to CRP and thus are not considered in this thesis. The three remaining categories encompass all FMF MOS readiness training within a given syllabus.

Each of the three categories contains one or more MOS qualifications. An individual progressing through his syllabus completes an area of MOS training to become qualified in that area. Each qualification reached represents an improvement in readiness and professional competence. Once the individual completes the qualification event for a position, he is *designated* in that position. For example, an MOS 7236 Marine might complete all events required for qualification as Air Intercept Controller. Once he completes the qualification event, the Commanding Officer signs his designation as Air Intercept Controller. Designation is merely an administrative endorsement by the Commanding Officer that the individual meets the requirements for qualification.

2. Events

By T&R definition, events consist of academics and performance. Academics may consist of preparatory study, informal or classroom instruction, and testing. Normally, students satisfy academic requirements in conjunction with performance of an event. Therefore, in the context of scheduling, schedulers assume that the individual accomplishes commensurate academic preparation and evaluation prior to performing an event (e.g., flying an aircraft training mission, controlling aircraft, etc., depending upon unit type).

3. Prerequisites

Each event may have one or more *prerequisite* events. For instance, within the MOS 7236 syllabus, providing tactical intercept control to a section (two aircraft) is a prerequisite to controlling a division (four aircraft). A graph of the resulting set of events and prerequisites describes the paths that a Marine may follow to qualifications. Figure 1 demonstrates such a graph for MOS 7210.

4. Refly Interval

Once competed, an event must be repeated within a specific time period in order for the individual to maintain currency in that event. The *refly interval* indicates the time

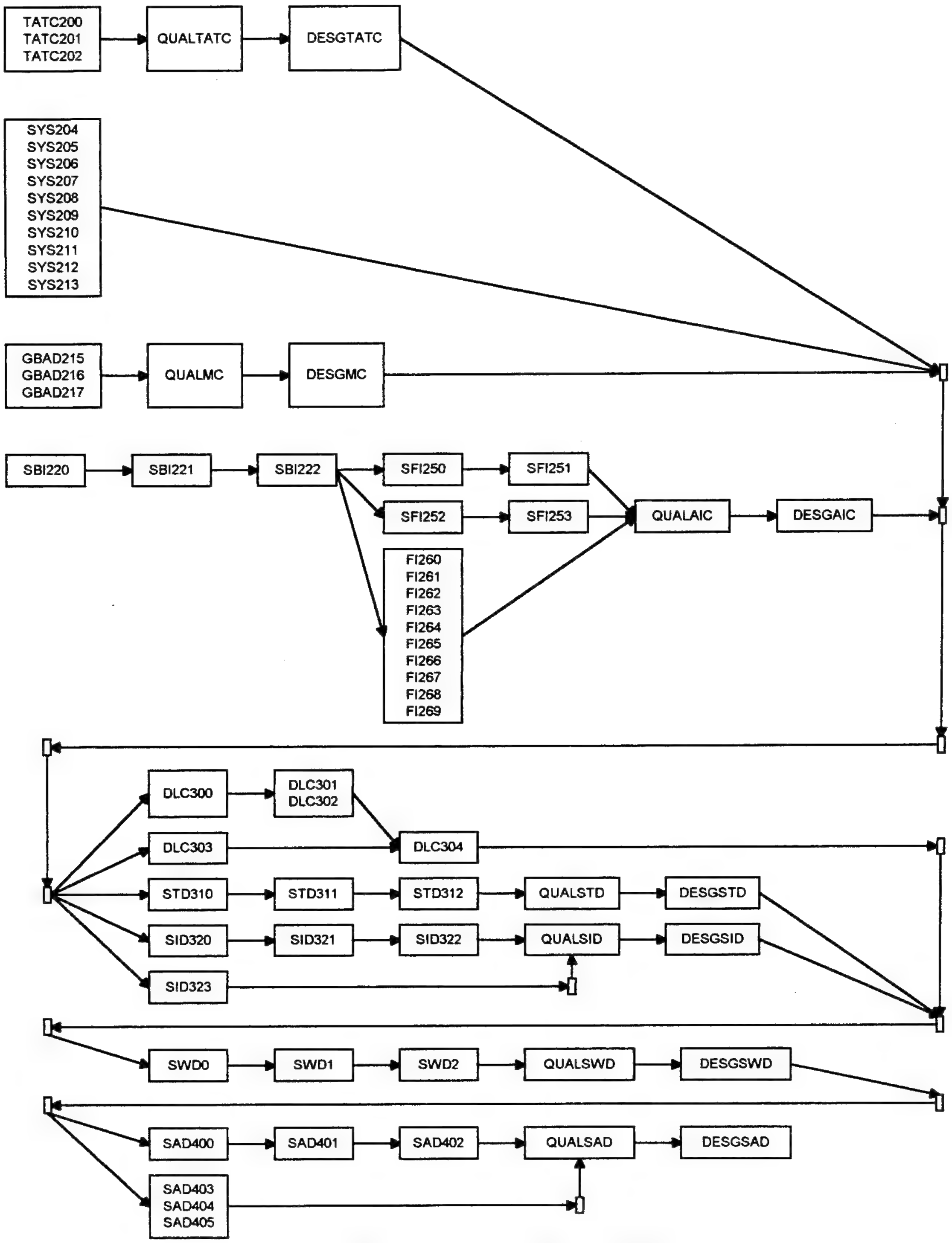

Figure 1. Training Event Graph for MOS 7210

from last completion until an individual's currency expires. If currency expires, the individual loses the CRP contribution of the event. However, if the event is repeated during the refly interval, his CRP remains unchanged, his currency updates, and his refly interval restarts.

5. Supervision

Once an individual qualifies in a crew position, he may complete supplementary training to become a designated supervisor of non-qualified individuals (students) in that same position. A supervisor must be current in the event performed by a student in order to be eligible to supervise the event. Both the supervisor and student update currency for an event performed by the student.

6. Chaining

An individual updates currency in multiple events through *chaining* earlier events in a syllabus sequence. This means that a Marine resets refly intervals for both the event performed or supervised and for (earlier, easier) events "chained" but not actually performed. For instance, suppose an MOS 7236 student completes division control for the first time. Consequently he gains CRP for division control and resets his refly interval for section control, a prerequisite event. A chaining graph resembles, but is not strictly equivalent to the inverse of the prerequisite graph. Individuals maintain currency through chaining by completing a small subset of events that require greater proficiency instead of repeating all elementary events.

7. CRP Calculation

Performance, supervision, and chaining increase or maintain CRP and update currency. When an individual performs an event for the first time or repeats one which is no longer current, his CRP increases by the event's contribution. For events repeated within the refly interval through performance, supervision, or chaining, CRP is

unchanged and currency updates. Therefore, an individual's CRP is the sum of CRP contributions over all his current events, plus the Combat Capable baseline CRP of 60%.

C. CURRENT MANAGEMENT PRACTICES

Despite improvements in data management and reporting of readiness data, squadron still implement the T&R Program inefficiently. Due to these inefficiencies, squadrons still cannot do a very good job of creating efficient and equitable schedules.

1. Manual Scheduling in the FMF

Most FMF aviation units schedule, forecast, and plan training manually. Squadrons usually generate two types of schedules: "macro" and daily. One, two, or three month macro schedules are planning guides that indicate gross numbers of events by type to be accomplished by the unit within the time span. The schedule indicates either individual to event or event to time period (week, day, or half-day) assignments. When generating the schedule, the training staff checks prerequisites, currency, and personnel availability manually. Rarely do squadrons produce macro schedules that specifically assign an individual to an event to a time period due to the effort required. Most macro schedules ignore many of the T&R Program and personnel availability constraints and thereby provide only a rough guide to making actual assignments. At the daily level, schedulers manually assign individuals to events and specific times, checking prerequisite, currency, and availability requirements for that day only.

The training staff estimates future readiness from ATRIMS data coupled with manual macro schedules. They project CRP accumulations and add them to current CRPs to estimate future CRPs often ignoring prerequisite, chaining, and availability implications. Training requirements are identified from "greaseboard" reports and programmed into macro schedules.

Schedulers write rough equity into the macro schedule. However, since the macro schedule does not capture all of the Program and personnel availability constraints, many changes occur during execution of the schedule. The scheduler incorporates these changes into the daily schedule and attempts to make assignments equitable based on what he can recall about the content of recent daily schedules. Over time, the resulting assignments are, at best, only roughly equitable.

2. Deficiencies

The manual nature of the current system hinders efficiency in many ways that can be improved.

a. Time

Despite the automation of record keeping, FMF squadrons still schedule manually. Manual scheduling is manpower-intensive and time-consuming. Manual consideration of program requirements, prerequisites, and availability is tedious and prone to error. Also, the process consumes the time of the squadron technical training staff that would be put to better use conducting or supervising training. Manual scheduling hampers effective training management.

b. Efficiency

The complexity of the assignment scheme retards effective manual scheduling. Often, the primary goal of schedulers is merely to reach a feasible solution. Chaining, supervisory credit, prerequisite paths, and availability all conspire to hide optimality from the scheduler. Resulting sub-optimal schedules hinder maximization of readiness.

c. Long-Term Effectiveness

While the impact of inefficient schedules may not be obvious within daily schedules, a sub-optimal schedule affects every future schedule adversely to some

degree. Cumulatively over time, sub-optimal schedules reduce readiness, forcing units to schedule even more events to maintain an effective T&R program. Therefore, sub-optimal scheduling wastes scarce resources, adversely affects readiness, and threatens the long-term effectiveness of a unit's T&R program.

d. Equity

Equity is inadequately maintained within current procedures for three reasons. First, since equity is secondary to readiness, enforcement of equity is usually abandoned when a scheduler encounters a complex scheduling situation. Second, even if planned in a macro schedule, equity is difficult to track and ensure among daily schedules. Finally, conscious or unconscious favoritism by schedulers diminishes equity.

D. OBJECTIVE OF CURRENT RESEARCH

This thesis develops a bicriteria mixed integer programming model that produces a ninety day training schedule that maximizes a combination of readiness and equity. The model enforces Program requirements and personnel availability constraints. The resulting schedules are optimal with respect to a combination of readiness and equity of both workload and individual progression. Additionally, the model reports readiness levels based on execution of the schedule, calculates for each event type the potential impact of adding one event to the schedule, and determines personnel underuse by time period. This thesis presents the underlying model for optimal scheduling and automated training management and implements the model for one specific type of unit, the Marine Air Control Squadron (MACS).

E. THESIS OUTLINE

Chapter II explores related models developed by other researchers. Chapter III presents the mathematical formulation a T&R scheduling model. Chapter IV describes the results of computational testing on a specific instance of the problem, and Chapter V

gives conclusions and recommendations. The Appendix contains partial output from the model.

II. RELATED SCHEDULING MODELS

The following describes related scheduling models or alternative approaches to the scheduling problem described in Chapter I.

A. READINESS MAXIMIZATION IN AVIATION UNITS

Van Brabant (1993) presents an aviation training optimization model for Navy squadrons (Navy and Marine Corps aviation training are similarly structured). The model maximizes readiness subject to equity, aircraft per event requirements, and quarterly fuel allocation. All events within a mission area are weighted identically while mission areas are weighted according to the commander's preference. Resulting monthly schedules assign individuals to events and thus arrive at the numbers of events that must be performed in the month. Time periods are not modeled explicitly so that individual to event to time period assignments are not made. Elastic variables allow for violation of sortie per pilot and quarterly fuel constraints.

The emphasis of the Van Brabant model is towards determining training requirements, that is, generating macro one-month scheduling goals of event to pilot assignments. These assignments in turn must be scheduled daily until the scheduled goals are met.

B. EQUITY

1. Aviation Models

Van Brabant uses a goal programming approach (e.g., Chankong and Haimes, 1983) with elastic decision variables that measure deviation from equity and total unit sorties goals. He calculates the mean sortie per pilot over the month during preprocessing and that mean becomes the equity goal in the formulation. Unpenalized variation about the mean is allowed within bounds. The bounds are established by the

decision maker. Violation of these bounds is penalized. Van Brabant's model provides gross equity over the month without considering personnel availability.

2. Management Models

Mandell (1991) discusses a bicriteria mathematical programming model for providing decision makers with analytical tools to judge trade-offs between equity and effectiveness in public delivery systems. His example is the distribution of books among branches of a public library system. Mandell produces graphical decision aids such as a display of the *efficient frontier* that shows the trade-off between equity and effectiveness from his model. His formulation optimizes effectiveness and includes equity as a constraint limited by a parameter. By iterative variation of the parameter, he plots the efficient frontier for effectiveness versus equity. Mandell also notes alternate graphical presentations such as empirical quantile-quantile plots of decision variables at two points on the frontier.

C. EXPERT SYSTEMS

In contrast to mathematical programming approaches, other authors offer heuristic approaches to aviation training scheduling. O'Connor (1991) proposes an expert system designed to automate the "antiquated" greaseboard system and provide high quality scheduling with non-expert schedulers. He provides a prototype implementation with commercial database management software. Hodgkins (1992) follows a similar tack, building an application with a different relational database software. Both systems attempt to put as much information as possible at the fingertips of the scheduler to enable him to produce a more intelligent and efficient schedule. However, both are heuristics that duplicate some of the present record-keeping features of ATRIMS.

D. COMMERCIAL AIRCREW SCHEDULING

Set partitioning has been used for commercial aircrew scheduling for decades. Marsten and Shepardson (1981) review a handful of successful applications. In general the problem is to pair aircrews with trips that will cover all required flight legs while minimizing costs. During preprocessing, flight legs are linked together to generate *pairings*, or roundtrips, that originate from crew bases and satisfy crew rest restrictions. Formulated as an integer program over a moderate time horizon (up to one month), this combinatorial problem can be intractable for large instances, e.g., a large domestic airline. Graves et al. (1993) describe an elastic set partitioning approach employed by United Airlines that produces near-optimal solutions for large problems. Hoffman and Padberg (1993) use cutting planes within a branch and bound algorithm to optimally solve the set partitioning problems.

The process of combining legs into sequences could be applied to the T&R scheduling problem. Sequences of events could form pairings that would be assigned to individuals maximizing CRP gain. Training event sequences, however, are not as long or complex (combinatorially) as the sequence of flight legs in the aircrew problem. Therefore the problem can be formulated more directly.

E. ANOTHER EFFORT

Kawakami (1990) uses an integer programming approach to develop three aviation training scheduling models. The first two models address scheduling of aircraft commanders and "second pilots," respectively, within a single Japanese Maritime Self-Defense Force operational squadron. These formulations maximize assignments of pilots to "critical items" (based on impending loss of currency) subject to flight hours per day per pilot, events per day per pilot, and aircraft availability. These two models are solved independently and combined manually to produce a single unit schedule. The author considers linking the two models via pairing of pilots to "second pilots" too difficult and

accepts the resulting potential for suboptimal schedules. The third model deals with a USMC training squadron. In this type of non-FMF squadron, aircrew receive the entry level training that makes up the 60% baseline CRP. This type of training has unique structure and policy that are quite different from FMF squadrons. As a result, this model provides little insight into FMF training management.

All three models presented by Kawakami produce single day schedules. Optimization over a time horizon is not considered. In addition, equity is not included as an objective.

F. THIS EFFORT

This thesis builds primarily upon the efforts of Van Brabant and Kawakami using Mandell's guidance on graphical decision aids. The model in this thesis maximizes a combined function of both effectiveness and equity over a three month time horizon, at a half-day level of resolution, producing individual to event to time period assignments with consideration of personnel availability.

III. A T&R SCHEDULING MODEL

The T&R scheduling model for the MACS, detailed below, is a mixed integer program that maximizes a combination of readiness and equity over a time horizon of ninety days (in units of half-days) for a fixed set of events and time periods to be scheduled. The model enforces T&R Program policies (prerequisites, chaining, refly intervals, etc.), accounts for individual unavailability, and ensures supervision of students. The resulting schedule lists the individual to event to time period assignments of supervisors and students. Additional output identifies unused personnel in each time period, projected individual and unit CRP gains, resulting individual currency, and events that cannot be scheduled due to lack of personnel.

A. INDICES

1. Index Sets

t, t'	Time periods (half-days; t=0, 1, 2, ..., T);
$i, i' \in I$	Individuals;
$j, j', j'' \in E$	Events; and
g	Syllabus segment.

2. Index Subsets

$Student_j \subseteq I$	Individuals who are students for event j;
$Supervisor_j \subseteq I$	Individuals who are supervisors of event j; and
$Segment_g \subseteq E$	Events which form syllabus segment g.

B. DATA

1. T&R Program Policy Data

$Prereq_{jj'}$	Binary matrix of event prerequisites (1 if j is a prerequisite of j', and 0 otherwise);
$Chain_{jj'}$	Binary matrix of event chaining (1 if performing j chains credit for j', and 0 otherwise);
Crp_{ij}	Contribution of event j to individual i's CRP; and
$Expire_j$	Time periods until event j must be repeated to maintain currency (refly interval).

2. ATRIMS Data

$Current_{ij0}$	Time periods from t=0 until individual i's currency in event j expires; and
$EligEvnt_{ij}$	Binary indicator that is 1 if individual i is eligible to perform event j, and is 0 otherwise.

3. Personnel Availability Data

$Avail_{it}$	Binary indicator that is 1 if individual i is available at time t, and is 0 otherwise;
$Able_{ijj't}$	Binary indicator that is 1 if individual i's initial currency for event j expires prior to time t, thus prohibiting assignment of follow-on event j', and is 0 otherwise (i.e., 1 if $Avail_{it}$=1 and $Prereq_{jj'}$=1 and t>$\mathrm{Current}_{ij0}$, and 0 otherwise); and
$AbleSup_{ijt}$	Binary indicator that is 1 if supervisor i's initial currency in event j expires prior to time t, i.e., if $Avail_{it}$=1 and $i \in Supervisor_j$ and t>$Current_{ij0}$, and 0 otherwise.

4. Event List Data

$Event_{jt}$	Number of events of type j to be scheduled at time t;

5. Model Parameters

λ	Objective function parameter that is varied to investigate the trade-off between the two criteria, equity and readiness;
$CostDrop$	Penalty cost for failing to schedule an event;
$AssignHi_{ig}$	Upper limit on total unpenalized assignments of individual i to events in syllabus segment g;
$AssignLo_{ig}$	Lower limit on total unpenalized assignments of individual i to events in syllabus segment g;
$GCrpHi_{ig}$	Upper limit on total unpenalized CRP gain by individual i from events in syllabus segment g; and
$GCrpLo_{ig}$	Lower limit on total unpenalized CRP gain by individual i from events in syllabus segment g.

C. VARIABLES

To help distinguish decision variables from data, decision variables are typed in all capitals.

$$ASSIGN_{ijt} = \begin{cases} 1 \text{ if event } j \text{ is assigned to individual } i \text{ at time } t \\ 0 \text{ otherwise;} \end{cases}$$

$$SUPER_{ijt} = \begin{cases} 1 \text{ if individual } i \text{ supervises event } j \text{ at time } t \\ 0 \text{ otherwise;} \end{cases}$$

$$CREDIT_{ij} = \begin{cases} 1 \text{ if individual } i \text{ gets credit for event } j \\ 0 \text{ otherwise;} \end{cases}$$

$ASNOVER_{ig}$	Number of performance and supervisory assignments above individuals i's upper limit on assignments in syllabus segment g;
$ASNUNDER_{ig}$	Number of performance and supervisory assignments below individual i's lower limit on assignments in syllabus segment g;

$CREDOVER_{ig}$	CRP gain of individual i above his upper limit on total CRP gain in syllabus segment g; and
$CREDUNDER_{ig}$	CRP gain of individual i below his lower limit on total CRP gain in syllabus segment g.

D. FORMULATION

Maximize $READINESS\text{-}\lambda * INEQUITY$

where

$$READINESS \equiv \sum_{ij} (Expire_j - Current_{ij0}) * Crp_{ij} * CREDIT_{ij}$$

$$-\sum_{jt} CostDrop * \left(Event_{jt} - \sum_{i} ASSIGN_{ijt} \right)$$

and

$$INEQUITY \equiv \sum_{ig} (ASNOVER_{ig} + CREDOVER_{ig} + ASNUNDER_{ig} + CREDUNDER_{ig})$$

Subject to

$$\sum_{i} ASSIGN_{ijt} \leq Event_{jt} \qquad \forall j, t \tag{1}$$

$$\sum_{j} \left(ASSIGN_{ijt} + SUPER_{ijt} \right) \leq 1 \qquad \forall i, t \tag{2}$$

$$ASSIGN_{ij't} \leq \sum_{t'<t}\left(ASSIGN_{ijt'}+SUPER_{ijt'}\right) +$$

$$\sum_{j''}\sum_{\substack{t'<t \text{ and} \\ t'<Current_{ij0}}} Chain_{j''j} * \left(ASSIGN_{ij''t'}+SUPER_{ij''t'}\right)$$

$$\forall (i,j,j',t) \in Able_{ijj't} \qquad (3)$$

$$SUPER_{ijt} \leq \sum_{t'<t}\left(ASSIGN_{ijt'}+SUPER_{ijt'}\right) +$$

$$\sum_{j'}\sum_{\substack{t'<t \text{ and} \\ t'<Current_{ij0}}} Chain_{j'j} * \left(ASSIGN_{ij't'}+SUPER_{ij't'}\right)$$

$$\forall (i,j,t) \in AbleSup_{ijt} \qquad (4)$$

$$CREDIT_{ij} \leq \sum_{t}(ASSIGN_{ijt} + SUPER_{ijt}) +$$

$$\sum_{j'}\sum_{t<Current_{ij0}} Chain_{jj'} * (ASSIGN_{ij't} + SUPER_{ij't}) \qquad \forall i,j \qquad (5)$$

$$\sum_{i \in Student_j} ASSIGN_{ijt} = \sum_{i \in Supervisor_j} SUPER_{ijt} \qquad \forall j,t \qquad (6)$$

$$\sum_{j \in Segment_g}\sum_{t} ASSIGN_{ijt} + SUPER_{ijt} \leq AssignHi_{ig} + ASNOVER_{ig}$$

$$\forall i,g \qquad (7)$$

$$\sum_{j \in Segment_g}\sum_{t} ASSIGN_{ijt} + SUPER_{ijt} \geq AssignLo_{ig} - ASNUNDER_{ig}$$

$$\forall i,g \qquad (8)$$

$$\sum_{j \in Segment_g} CRP_{ij} * CREDIT_{ij} \leq GCrpHi_{ig} + CREDOVER_{ig} \qquad \forall i,g \qquad (9)$$

$$\sum_{j \in Segment_g} CRP_{ij} * CREDIT_{ij} \geq GCrpLo_{ig} - CREDUNDER_{ig} \qquad \forall i, g \qquad (10)$$

$$ASSIGN_{ijt} \in \{0,1\} \qquad \forall i,j,t$$

$$SUPER_{ijt} \in \{0,1\} \qquad \forall i,j,t$$

$$CREDIT_{ij} \in \{0,1\} \qquad \forall i,j$$

$$ASNOVER_{ig} \geq 0 \qquad \forall i,g$$

$$ASNUNDER_{ig} \geq 0 \qquad \forall i,g$$

$$CREDOVER_{ig} \geq 0 \qquad \forall i,g$$

$$CREDUNDER_{ig} \geq 0 \qquad \forall i,g$$

The objective function is composed of two parts, *READINESS* and *INEQUITY*. The parameter λ is varied to investigate the trade-off between the two goal of maximizing *READINESS* and minimizing *INEQUITY*, i.e., maximizing equity.

The *READINESS* portion of the objective function contains two parts. The first summation of *READINESS* measures readiness by summing CRP for all credited events over all individuals and events. Each CRP item is weighted by the difference between expiration and currency to favor scheduling event-individual pairs which are closer to expiration of currency. The second summation of *READINESS* merely encourages scheduling of excess events (i.e., events that do not provide additional readiness value because there are more events of a given type to be scheduled than individuals who need to be assigned that event type within the time horizon). This term remains relatively constant for all values of λ and does not affect the trade-off between readiness and equity. It penalizes unscheduled events to encourage scheduling of all events in the event list.

The *INEQUITY* portion of the objective function measures inequity as the sum of all violations of equity bounds on total assignments and CRP gain.

Constraints (1) and (2) limit assignments to existing events and ensure individuals are assigned to at most one event per time period. Constraints (1) limit the total number of performance assignments among all individuals, for a given time period and event type, to the total number of events of that type available at that time. Constraints (2) limit each individual to performing or supervising at most one event per time period.

Constraints (3), (4), (5) and (6) enforce T&R Program policies. Constraints (3) ensure that T&R Program prerequisite requirements are satisfied. For available individuals, these constraints are created only if either the prerequisite event had never been performed or prerequisite currency would have expired based on initial currency. Thus, constraints (3) ensure that an individual performs all expired or never performed prerequisite events prior to assignment of a follow-on event. Constraints (4), in a manner similar to constraints (3), guarantee that a supervisor is current in an event he might supervise. Constraints (5) credit each individual with CRP contributions for events performed, supervised, or chained through either performance or supervision prior to expiration. Constraints (6) require that a supervisor be paired with each student assigned to an event.

Constraints (7), (8), (9), and (10) drive equity among individuals with respect to total assignments and CRP gain over all events in each syllabus segment. Deviations from limits are penalized in the objective function and help to ensure equity.

1. Calculation of Equity Bounds on Assignments

The calculation for each individual's workload target in each syllabus segment uses the following relationship:

$$WorkTgt_{ig} = \sum_{j \in Segment_g} \sum_t Event_{jt} * \frac{\sum_{j \in Segment_g} \sum_t CanDo_{ijt}}{\sum_{i'} \sum_{j \in Segment_g} \sum_t CanDo_{i'jt}}$$

where

$$CanDo_{ijt} = \begin{cases} 1 \text{ if } (Avail_{it} = 1) \wedge (EligEvnt_{ij} = 1) \wedge (Event_{jt} > 0) \\ 0 \text{ otherwise} \end{cases}$$

$WorkTgt_{ig}$ is based on the number of time periods during which the individual is available and eligible (for assignment to events in segment g) and the number of events in the segment that must be scheduled. Each individual gets his "fair share" of assignments during the time both that he is available and there exist events for which he is eligible. Bounds on workload equity, $AsnHi_{ig}$ and $AsnLo_{ig}$, allow a tolerance about the work target rounded up and down, respectively.

2. Calculation of Equity Bounds on Individual CRP Gain

The interactions of individual progression, availability, prerequisites, and chaining make determination of appropriate bounds on CRP gain difficult. One upper bound on CRP gain within a segment by an individual is the sum of CRPs for events never performed or noncurrent, across all events in a segment during time periods that an individual is available. After solving the program with bounds $GCrpHi_{ig}$ and $GCrpLo_{ig}$ based on fractions of maximum CRP gain, the bounds can be refined by tightening them further. This process could continue until further tightening does not improve equity.

IV. COMPUTATIONAL TESTING

The T&R scheduling model was generated with GAMS (Brooke, et. al., 1992) and solved using the XA (Sunset Software Technology, 1993) solver on an IBM RISC-6000 Model 590, generally within 100 seconds. With parameters established during testing, an Intel 486DX2-50 personal computer produces a solution in under 10 minutes. ATRIMS, personnel availability, and training forecasts were collected from an FMF MACS. This chapter describes the MACS data, the model parameters, and the testing results.

A. DATA

ATRIMS, personnel availability, and training forecast data were collected from MACS-6 at Marine Corps Air Station Cherry Point, North Carolina. The test data set from the MACS contains some of the most difficult complexities encountered within the T&R Program: multiple MOSs in one unit, overlapping event lists between MOS syllabi, and relatively long progression paths. The Squadron had 36 personnel in three MOSs covered by the T&R Program: 11 MOS 7210 Air Defense Control Officers (ADCOs), 13 MOS 7236 Tactical Air Defense Controllers (TADCs), and 12 MOS 7234 Air Control Electronics Operators (ACEOs). Two of the MOS syllabi, ADCO and TADC, overlap in Combat Ready, Combat Capable, and Full-Combat Qualification Training. They differ only in event CRP contribution.

Marines in MOS ACEO assist or are subordinate to an ADCO or TADC in all training events. Even though the ADCO/TADC and ACEO event lists are different, every ACEO event is dependent upon an ADCO/TADC event. For example, if an ADCO/TADC event must be canceled for lack of personnel, the dependent ACEO event must also be canceled. In contrast, an ADCO/TADC event can be completed regardless of whether its dependent ACEO event is completed.

Because of this one way dependency, the two problems can be separated and solved sequentially (i.e., solve the ADCO/TADC subproblem, delete resulting canceled ACEO events from the ACEO subproblem, and solve the reduced ACEO subproblem). The two subproblem solutions are then joined into a single solution for the unit. The number of canceled events from combining the solutions indicates how much better the schedule could be if the problems are not separated. In the worst case of the instance tested, 13 ADCO/TADC events were not scheduled which caused cancellation of only four of the 156 ACEO events with total CRP contribution of only 1.2 of a total 66.6. This minimal worst-case loss of efficiency demonstrates the bounds on improvement possible in a combined, completely optimal model.

The ACEO subproblem is also easier to solve than the ADCO/TADC subproblem. Since ADCO or TADC may supervise an ACEO event in the absence of an ACEO supervisor, ACEO students are not strictly paired to ACEO supervisors. As a result, constraints (6) may be relaxed to an inequalities (i.e., allowing fewer supervisors than students). In addition, the ACEO subproblem is generally smaller. Table 1 demonstrates the sizes of the subproblems from the MACS data. Since the ACEO subproblem is smaller than the ADCO/TADC subproblem and constraints (6) may be relaxed, the ACEO subproblem is the easier of the two subproblem instances to solve. Therefore, the following discussion focuses on the ADCO/TADC subproblem.

Subproblem	***Number of Individuals***	***Number of Events in Syllabus***	***Number of Events to be Scheduled***	***Number of Segments in Syllabus***
ADCO/TADC	24	69	257	3
ACEO	12	46	156	3
Total	36	115	413	6

Table 1. Relative size comparison of ADCO/TADC and ACEO subproblems showing that the ACEO subproblem is equal or smaller in all dimensions.

The ADCO/TADC common syllabus can be divided into three segments: Weapons Controller (WC), Senior Weapons Director (SWD), and Senior Air Director (SAD). Table 2 lists the events, CRP contributions and refly intervals for the WC segment. Events without refly intervals do not require repetition. Tables 3 and 4 list the same information for the SWD and SAD segments, respectively. Table 5 lists individuals by decreasing initial CRP, indicating MOS and availability percentages during the time periods scheduled.

B. MODEL PARAMETERS

1. Objective Function Parameters

Two parameters appear in the objective function: λ which is varied to explore the trade-off between readiness and equity, and CostDrop which encourages scheduling of excess events. λ was varied between 10-6 and 106. CostDrop was set at 100. This empirically determined value is large enough to encourage scheduling of excess events while not interfering with the trade-off between readiness and equity.

2. Equity Bound Parameters

During testing, individual bounds in each segment on workload and CRP gain were refined. These bounds appear in constraints (7), (8), (9) and (10). Violations of these bounds force equity deviation variables to take on positive values. Positive values of these deviation variables are penalized in the objective function, discouraging inequity.

a. Workload

Workload bounds $AsnHi_{ig}$ and $AsnLo_{ig}$ allow unpenalized variation of workload about $WorkTgt_{ig}$ for each individual in each segment. During testing it was determined that 5% variation produced sufficiently tight bounds (i.e., $AsnHi_{ig} = \lceil 1.05 * WorkTgt_{ig} \rceil$ and $AsnLo_{ig} = \lfloor 0.95 * WorkTgt_{ig} \rfloor$). Using a smaller tolerance to define these bounds caused longer solution times without improving equity.

Event	*ADCO CRP*	*TADC CRP*	*Expire (Months)*
TATC200	0.12	0.12	12
TATC201	0.12	0.12	-
TATC202	0.12	0.12	-
QUALTATC	1.00	1.00	36
DESGTATC	1.00	1.00	-
SYS204	0.12	0.12	6
SYS205	0.12	0.12	6
SYS206	0.12	0.12	12
SYS207	0.12	0.12	12
SYS208	0.12	0.12	6
SYS209	0.12	0.12	6
SYS210	0.12	0.12	6
SYS211	0.12	0.12	6
SYS212	0.12	0.12	6
SYS213	0.12	0.12	6
GBAD215	0.12	0.12	12
GBAD216	0.12	0.12	12
GBAD217	0.12	0.12	24
QUALMC	1.00	1.00	36
DESGMC	1.00	1.00	-
SBI220	0.12	0.12	12
SBI221	0.12	0.12	12
SBI222	0.12	0.12	12
SFI250	0.12	0.12	-
SFI251	0.12	0.12	12
SFI252	0.12	0.12	12
SFI253	0.12	0.12	12
FI260	0.12	0.12	12
FI261	0.12	0.12	12
FI262	0.12	0.12	12
FI263	0.12	0.12	12
FI264	0.12	0.12	12
FI265	0.12	0.12	12
FI266	0.12	0.12	12
FI267	0.12	0.12	12
FI268	0.12	0.12	12
FI269	0.12	0.12	12
QUALAIC	1.00	1.00	36
DESGAIC	1.00	1.00	36

Table 2. List of events, CRP contributions, and refly intervals for syllabus segment "WC."

Event	*ADCO CRP*	*TADC CRP*	*Expire (Months)*
DLC300	0.60	0.82	36
DLC301	0.60	0.82	36
DLC302	0.60	0.82	36
DLC303	0.60	0.82	36
DLC304	0.60	0.82	36
STD310	0.60	0.82	24
STD311	0.60	0.82	24
STD312	0.60	0.82	24
QUALSTD	1.00	2.00	36
DESGSTD	1.00	1.00	-
SID320	0.60	0.82	24
SID321	0.60	0.82	24
SID322	0.60	0.80	24
SID323	0.60	-	-
QUALSID	1.00	2.00	36
DESGSID	1.00	1.00	-
SSWD0	0.60	3.00	24
SSWD1	0.60	3.00	24
SWD2	0.60	3.00	24
QUALSWD	1.00	5.00	36
DESGSWD	1.00	1.00	-

Table 3. List of events, CRP contributions, and refly intervals for syllabus segment "SWD."

Event	*ADCO CRP*	*TADC CRP*	*Expire (Months)*
SSAD400	1.29	-	24
SSAD401	1.29	-	24
SSAD402	1.29	-	24
SAD403	1.29	-	24
SAD404	1.29	-	24
SAD405	1.29	-	24
SAD406	1.30	-	24
QUALSAD	5.00	-	36
DESGSAD	1.00	-	-

Table 4. List of events, CRP contributions, and refly intervals for syllabus segment "SAD."

Individual	***MOS***	***Availability %***	***Initial CRP***
Reynolds	ADCO	100	99.88
Wood	TADC	76	99.76
Bragg	TADC	100	99.64
Rosecrans	ADCO	100	99.64
Dodge	TADC	76	99.40
Dahlgren	ADCO	100	99.04
Foote	TADC	76	87.52
Burnside	TADC	83	82.06
Tod	TADC	76	78.94
Chase	TADC	100	77.88
Du Pont	TADC	66	74.20
Butler	ADCO	76	74.00
Canby	TADC	100	72.26
Heth	TADC	100	71.42
Fox	TADC	76	69.26
Wade	ADCO	100	63.60
Shelby	ADCO	75	63.36
Mason	ADCO	100	63.12
Cobb	ADCO	100	62.28
Burnside	ADCO	100	61.56
Booth	ADCO	100	61.32
Adams	ADCO	100	61.20
Hancock	TADC	76	60.96
Hicks	TADC	98	60.72

Table 5. List of individuals, MOSs, availability percentages, and initial CRPs. Individuals are listed in order of decreasing initial CRP.

Individual workload bounds are calculated only for the most advanced segment (least advanced is WC, most advanced is SAD) for which the individual is eligible. Since greatest readiness improvement results from events in the individual's most advanced segment, and an individual accrues most lower segment credit through supervision, lower segment bounds are unnecessary.

b. CRP Gain

Equity bounds on CRP gain are based on percentages of maximum CRP gain possible (or $MaxCRPGain_{ig}$.) by an individual in a segment (i.e., if all events in the

event list are available to the individual). $MaxCRPGain_{ig}$ is calculated during preprocessing and the percentages are refined during testing iterations. The bounds are tightened until further tightening fails to reduce inequity. Table 6 shows the final multipliers applied to maximum CRP gain to produce CRP gain bounds $GCrpHi_{ig}$ and $GCrpLo_{ig}$.

Syllabus Segment	***Upper Bound Multiplier***	***Lower Bound Multiplier***
WC	0.28	0.08
SWD	0.32	0.12
SAD	0.10	0.00

Table 6. CRP gain multipliers applied to $MaxCRPGain_{ig}$ in order to produce equity bounds $GCrpHi_{ig}$ and $GCrpLo_{ig}$.

Table 7 tabulates workload and CRP gain bounds for syllabus segment WC. Tables 8 and 9 tabulate the bounds for SWD and SAD, respectively.

Individual	*AsnHi*	*AsnLo*	*GCrpHi*	*GCrpLo*
Reynolds	-	-	0.01	0.00
Dahlgren	-	-	0.05	0.00
Rosecrans	-	-	0.04	0.00
Wood	-	-	0.00	0.00
Butler	-	-	0.00	0.00
Bragg	-	-	0.00	0.00
Tod	-	-	0.00	0.00
Canby	-	-	0.55	0.21
Dodge	-	-	0.00	0.00
Burnside	-	-	0.04	0.01
Chase	-	-	0.44	0.16
Du Pont	-	-	0.08	0.03
Foote	-	-	0.00	0.00
Adams	15	12	1.41	0.40
Booth	15	12	1.38	0.39
Cobb	15	12	1.31	0.37
Wade	15	12	1.24	0.36
Burnside	15	12	1.48	0.42
Mason	15	12	1.41	0.40
Shelby	11	9	1.18	0.34
Heth	15	12	0.84	0.24
Fox	11	9	0.59	0.17
Hicks	14	12	1.49	0.43
Hancock	11	9	1.25	0.36

Table 7. Equity bound parameters for syllabus segment "WC." Assignment equity bounds apply only to "WC" segment students.

Individual	*AsnHi*	*AsnLo*	*GCrpHi*	*GCrpLo*
Reynolds	-	-	0	0
Dahlgren	-	-	0	0
Rosecrans	-	-	0	0
Wood	-	-	0	0
Butler	3	2	2.18	0.82
Bragg	4	3	0	0
Tod	3	2	5.91	2.22
Canby	4	3	6.64	2.49
Dodge	3	2	0	0
Burnside	3	2	4.63	1.74
Chase	4	3	5.64	2.12
Du Pont	3	2	2.71	1.02
Foote	3	2	3.52	1.32

Table 8. Equity bound parameters for syllabus segment "SWD." Assignment equity bounds apply only to "SWD" segment students. "WC" segment students are not listed because they are not eligible for "SWD" segment events.

Individual	*AsnHi*	*AsnLo*	*GCrpHi*	*GCrpLo*
Reynolds	25	22	0	0
Dahlgren	25	22	0	0
Rosecrans	25	22	0	0
Wood	18	16	0	0

Table 9. Equity bound parameters for syllabus segment "SAD." "WC" and "SWD" segment students are not listed because they are not eligible for "SAD" segment events.

C. RESULTS

The model produces optimal schedules with respect to a combination (based on the trade-off parameter λ) of readiness, and equity with respect to individual workload and CRP gain. The schedule satisfies T&R Program prerequisite, chaining, currency, qualification, and supervision requirements and explicitly accounts for personnel availability. The Appendix contains selected output from a model solution.

Figure 2 illustrates the trade-off between *READINESS* and *INEQUITY*. The dashed line indicates optimal *READINESS* with λ=0. Within the objective function discussed in Chapter III, λ was varied to establish an efficient frontier for this, essentially, bicriteria problem. Point A corresponds to unconstrained inequity (λ=0), Point B to minimally penalized inequity ($\lambda=10^{-6}$) and Point C to an example decision point on the efficient frontier (λ=215).

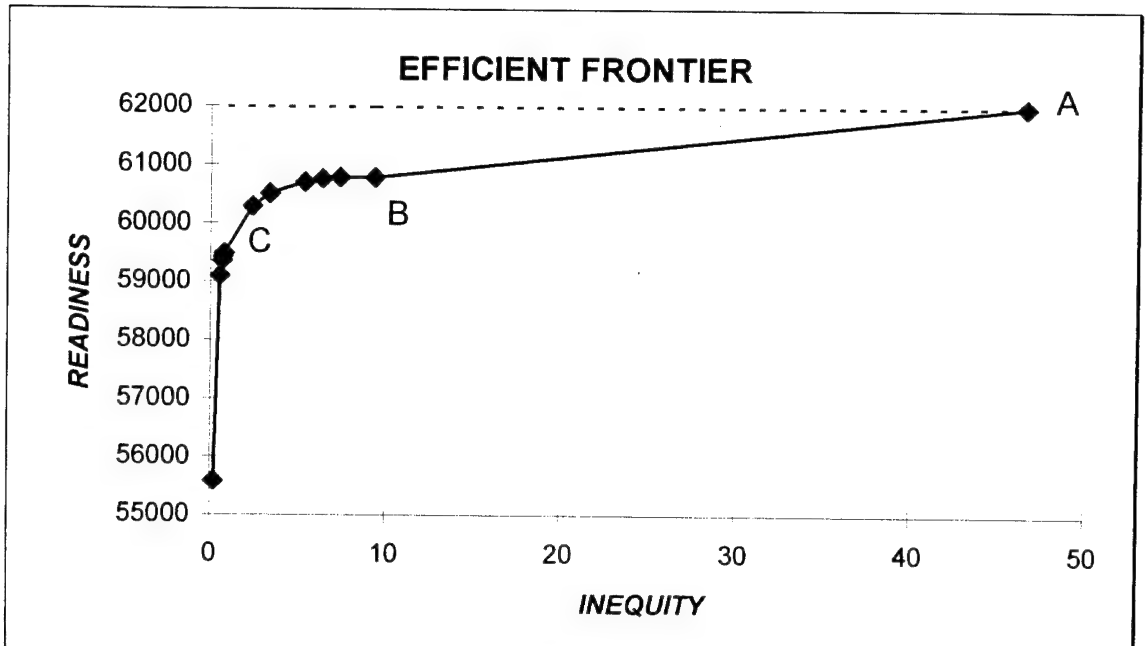

Figure 2. *INEQUITY* versus *READINESS* efficient frontier. Point A corresponds to no equity constraints, Point B to minimal equity constraints, and Point C to an example trade-off decision point.

Figure 3 illustrates the trade-off between total unit CRP gain and *INEQUITY*. The dashed line indicates optimal total unit CRP gain without equity constraints. Total CRP gain is the sum of all individual CRP gains. Points A, B, and C match those in the previous figure.

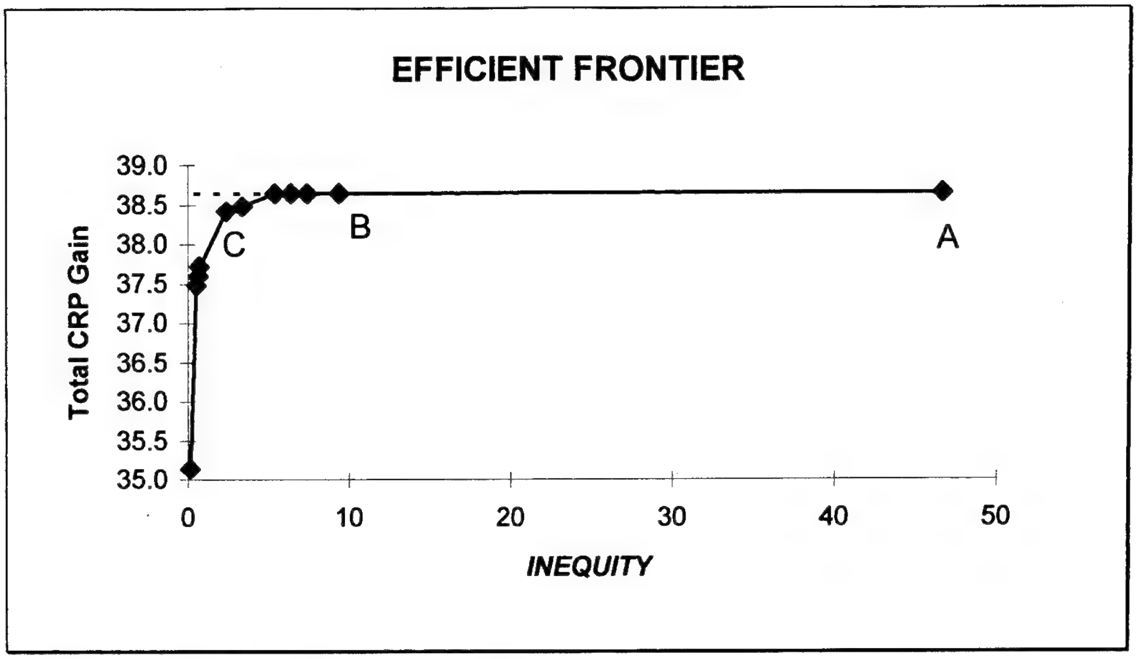

Figure 3. Inequity versus total CRP gain efficient frontier. Point A corresponds to no equity constraints, Point B to minimal equity constraints, and Point C to an example trade-off decision point.

Figure 4 shows a standard box plot (e.g., Chambers, et al., 1983) comparison of variation in individual workload for all three segments at three points on the efficient frontier. The three points indicated in Figures 2 and 3 correspond to the Run numbers on the box plots of Figure 4. The box plots show reduction in workload variance among individuals as a function of increasing emphasis on equity. The aberration in segment SWD on run three was caused by one individual at 28% of $WorkTgt_{ig}$. All others fell between 4% and 16%.

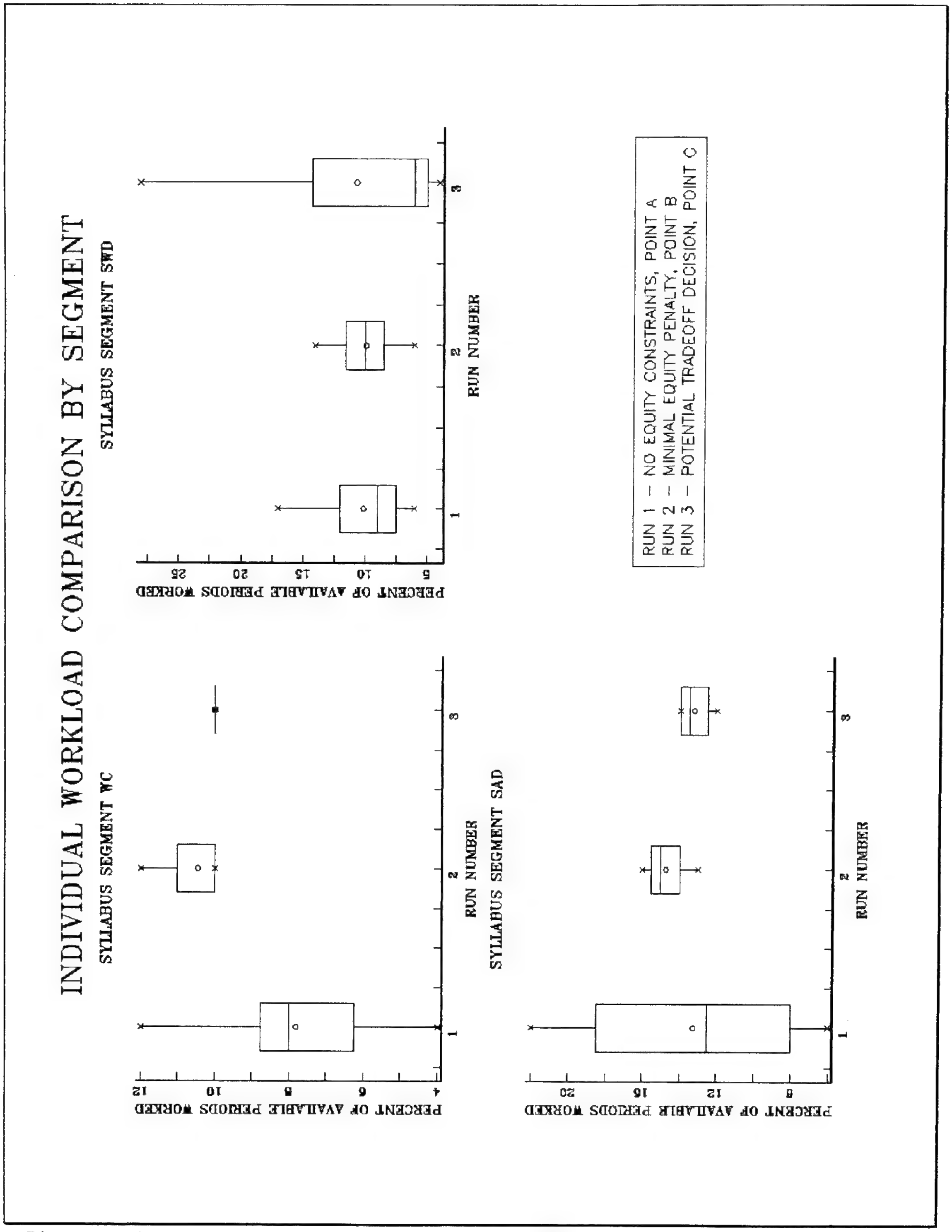

Figure 4. Comparison of individual workloads within each segment at three points on the efficient frontier.

Figure 5 illustrates a box plot comparison of CRP gain variation among individuals in each segment at three decision points on the efficient frontiers. Again, a decrease in variation is brought about by increasing emphasis on equity.

D. SUMMARY OF RESULTS

With the trade-off chosen by the user, the model produces optimal schedules with respect to a combination of readiness and equity. Even minimal values of λ cause significant reductions in inequity. However, increasing λ to decrease inequity further yields little additional benefit while causing accelerating decreases in readiness.

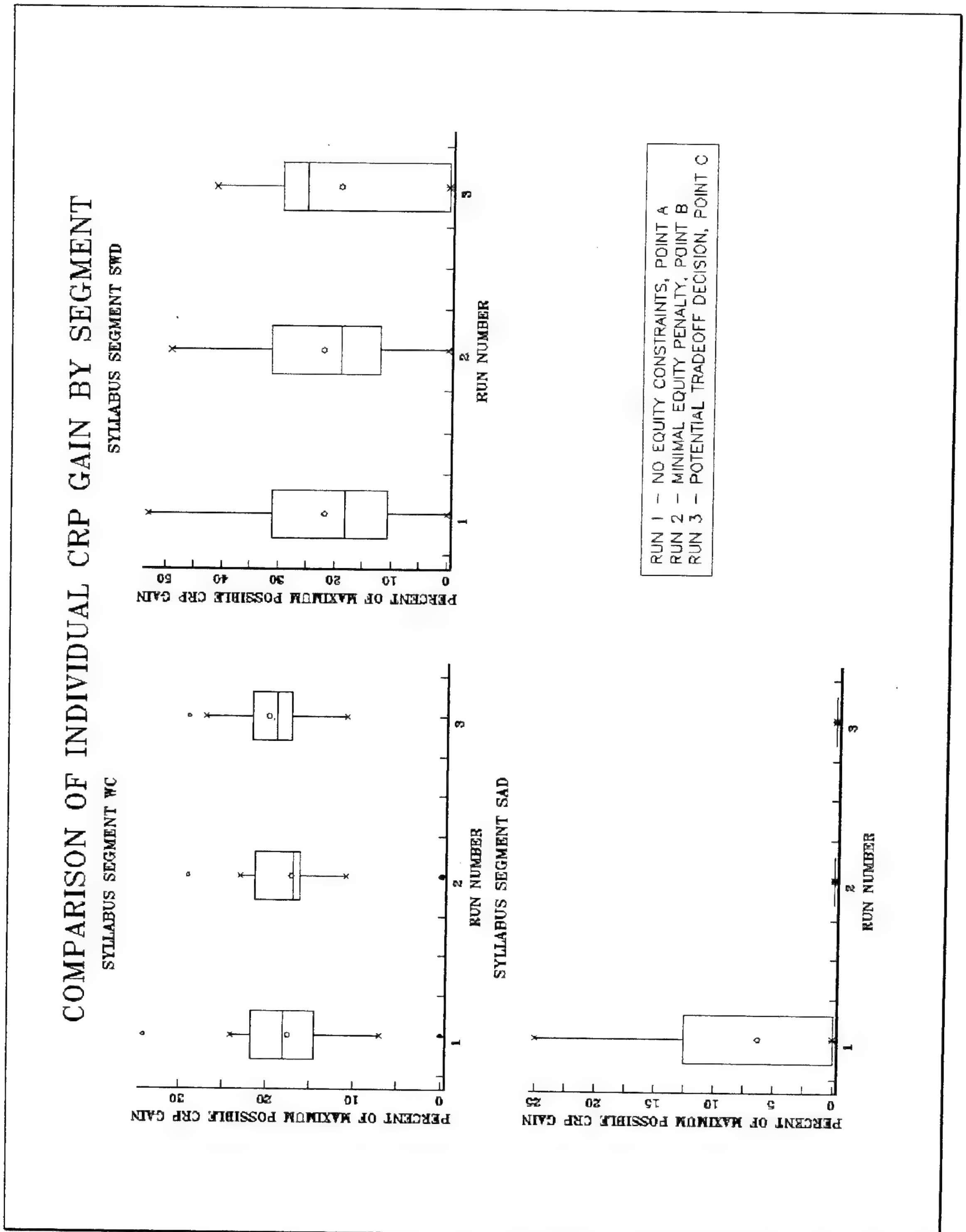

Figure 5. Comparison of individual CRP gain within each segment at three points on the efficient frontier.

V. CONCLUSIONS

Given a trade-off decision by the user, the T&R scheduling model is successful in optimizing a combination of readiness and equity in the schedules it produces. Scheduling with the model on a PC is much faster than manual scheduling. It uses input from an existing automated database and produces other useful training management information that was previously generated and maintained manually. With explicit individual-event-time period assignments, the schedule provides planners with much more information than was available using heuristically derived macro schedules.

The test data set from the MACS illustrates one of the most complex situations encountered within the T&R Program: multiple MOSs in one unit, overlapping event lists between MOS syllabi, and relatively long progression paths. The T&R scheduling model is applicable to other unit instances by simply inputting data and running the program a handful of times to establish model parameters.

The model could be improved by adding a user interface. The interface would automate the transfer of data from ATRIMS, simplify the input of personnel availability, and generate the model for the solver. In addition, various graphical decision aids and model output reports could be produced to simplify training decisions. The interface could also automate the determination of model parameters.

APPENDIX: SELECTED OUTPUT

This Appendix contains partial output from the model solution at point C identified in Chapter IV.

The model outputs individual to event to time period assignments for qualified individuals, students and supervisors. Only a sample is shown since all output would require over 40 pages. Figure 6 demonstrates model output of qualified individual and student assignments. Figure 7 demonstrates model output of supervisory assignments.

---- 1865 VARIABLE ASSIGN.L 1 if event j is assgined to individual i at time t

	3	4	5	6	7
HETH .SBI220		1.00			
CHASE .SYS208			1.00		
HICKS .FI264					1.00
REYNOLDS.SAD403				1.00	
DAHLGREN.SAD403		1.00			1.00
ROSECRAN.SAD403	1.00		1.00		
BOOTH .SYS205			1.00		
BOOTH .FI263					1.00
COBB .SBI220				1.00	
MASON .FI260	1.00				
MASON .FI264		1.00			

+	8	9	10	11	12
CANBY .SYS206		1.00			
CANBY .SYS209					1.00
HICKS .SFI252	1.00				
REYNOLDS.SAD403	1.00				
DAHLGREN.SBI222			1.00		
DAHLGREN.DLC300	1.00				
DAHLGREN.SAD403				1.00	
ROSECRAN.SAD403		1.00	1.00		1.00
ADAMS .SYS207					1.00
ADAMS .SFI250	1.00				
COBB .SBI222				1.00	
BURNSIDE.SFI250	1.00				

Figure 6. Model output of qualified individual and student assignments. An entry of "1.00" indicates an individual to event to time period assignment.

---- 1866 VARIABLE SUPERVISE.L 1 if i supervises event j at time t

	3	4	6	7	8
BRAGG .SBI220		1.00			
BRAGG .SFI250					1.00
CHASE .SFI250					1.00
CHASE .FI260	1.00				
DUPONT .FI263				1.00	
DAHLGREN.SBI220			1.00		
ROSECRAN.FI264		1.00			

+	11	14	18	20	21
BRAGG .FI261				1.00	
CHASE .SBI220		1.00			
CHASE .FI260			1.00	1.00	
DUPONT .SBI222	1.00				
REYNOLDS.STD310					1.00
DAHLGREN.FI261			1.00		
DAHLGREN.SID320					1.00

Figure 7. Model output of supervisory assignments. An entry of "1.00" indicates a supervisor to event to time period assignment.

Figure 8 tabulates workload equity information. "ASSIGN" and "SUPER" indicate the total number of regular and supervisory assignments, respectively. "LOADTOTAL" is the sum of all assignments. "WORKPCT" is the percentage of all time periods containing events that the individual is eligible to perform, during which he is assigned an event. "ABLEPCT" is the percentage of time periods during which the individual is both available and eligible during which he is assigned an event. "ABLEPCT" is the measure of individual workload used in the model. The model penalizes values of "ABLEPCT" outside of the bounds $AssignHi_{ig}$ and $AssignLo_{ig}$.

Figure 9 tabulates CRP gain equity information. "BEFORE" and "AFTER" indicate individual CRP at t=0 and t>180, respectively. "DELTA" indicates expected CRP increase resulting from execution of the schedule. "MAXDELTA" is the upper bound on CRP gain based on individual availability and the event list scheduled. "MAXDELPCT" shows the percentage of the maximum possible CRP gain actually achieved within the schedule. "MAXDELPCT" is the measure of equity used in the model. The model penalizes values of "MAXDELPCT" outside of the bounds $GCrpHi_{ig}$ and $GCrpLo_{ig}$.

1932 PARAMETER LOAD			workload comparison		
	ASSIGN	SUPER	LOADTOTAL	WORKPCT	ABLEPCT
WOOD	16.00	6.00	22.00	0.16	0.13
BRAGG	2.00	18.00	20.00	0.11	0.13
TOD	2.00	3.00	5.00	0.04	0.05
CANBY	7.00	2.00	9.00	0.05	0.06
DODGE	1.00	3.00	4.00	0.03	0.04
HETH	10.00	2.00	12.00	0.07	0.10
BURNSIDE	5.00	27.00	32.00	0.21	0.28
CHASE	5.00	16.00	21.00	0.12	0.14
DUPONT	3.00	12.00	15.00	0.13	0.15
FOX	8.00	1.00	9.00	0.07	0.10
FOOTE	3.00	2.00	5.00	0.04	0.05
HICHS	12.00		12.00	0.07	0.10
HANCOCK	9.00		9.00	0.07	0.10
REYNOLDS	25.00	9.00	34.00	0.19	0.14
DAHLGREN	25.00	9.00	34.00	0.19	0.14
ROSECRAN	23.00	6.00	29.00	0.16	0.12
ADAMS	12.00		12.00	0.07	0.10
BUTLER	3.00	4.00	7.00	0.05	0.06
BOOTH	12.00		12.00	0.07	0.10
COBB	12.00		12.00	0.07	0.10
WADE	12.00		12.00	0.07	0.10
BURNSIDE	12.00		12.00	0.07	0.10
MASON	12.00		12.00	0.07	0.10
SHELBY	9.00		9.00	0.07	0.10

Figure 8. Workload equity information.

---- 1889 PARAMETER CALCCRP			crp comparison		
	BEFORE	AFTER	DELTA	MAXDELTA	MAXDELPCT
WOOD	99.76	99.76			
BRAGG	99.64	99.64		0.24	
TOD	78.94	84.94	6.00	18.46	0.33
CANBY	72.26	77.96	5.70	22.46	0.25
DODGE	99.40	99.40			
HETH	71.42	72.02	0.60	3.00	0.20
BURNSIDE	82.06	84.88	2.82	14.58	0.19
CHASE	77.88	85.64	7.76	19.00	0.41
DUPONT	74.20	76.66	2.46	8.70	0.28
FOX	69.26	69.26		2.12	
FOOTE	87.52	90.52	3.00	11.00	0.27
HICKS	60.72	61.84	1.12	5.32	0.21
HANCOCK	60.96	61.96	1.00	4.48	0.22
REYNOLDS	99.88	99.88		0.12	
DAHLGREN	99.04	99.04		0.48	
ROSECRAN	99.64	99.64		0.36	
ADAMS	61.20	62.16	0.96	5.04	0.19
BUTLER	74.00	75.80	1.80	6.80	0.26
BOOTH	61.32	62.04	0.72	4.92	0.15
COBB	62.28	63.64	1.36	4.68	0.29
WADE	63.60	64.08	0.48	4.44	0.11
BURNSIDE	61.56	62.52	0.96	5.28	0.18
MASON	63.12	64.08	0.96	5.04	0.19
SHELBY	63.36	64.08	0.72	4.20	0.17

Figure 9. CRP gain equity information.

Figure 10 lists events unscheduled due to personnel unavailability.

---- 1870 PARAMETER DIDNTDO		unscheduled events
	23	90
QUALMC		1.00
SFI253	1.00	
FI269		2.00
QUALAIC		4.00
DLC304		1.00
SID323		1.00
SAD401	1.00	
SAD406		1.00

Figure 10. List of unscheduled events.

Figure 11 identifies idle personnel during time periods one through five. This list highlights time periods when additional training could be added to the schedule. It could also be used as a planning guide for assignment of Marines to other duties.

|---- 1873 PARAMETER UNUSED idle personnel at time t

	1	2	3	4	5
BRAGG	1.00	1.00	1.00		1.00
CANBY	1.00	1.00	1.00	1.00	1.00
HETH	1.00	1.00	1.00		1.00
CHASE	1.00	1.00		1.00	
DUPONT	1.00		1.00		1.00
HICHS	1.00	1.00	1.00	1.00	1.00
REYNOLDS	1.00	1.00	1.00	1.00	1.00
DAHLGREN	1.00	1.00	1.00		1.00
ROSECRANS	1.00	1.00			
ADAMS	1.00	1.00	1.00	1.00	1.00
BOOTH	1.00	1.00	1.00	1.00	
COBB	1.00	1.00	1.00	1.00	1.00
WADE	1.00	1.00	1.00	1.00	1.00
BURNSIDE	1.00	1.00	1.00	1.00	1.00
MASON	1.00	1.00			1.00

Figure 11. List of idle personnel.

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